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GENERAL ATOMICS

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Mechanical Design and Fabrication of the Lower Divertor for DIII-D*

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***Abstract*—The lower divertor of the DIII-D tokamak is being modified to provide improved density control of the tokamak plasma during operation in a high triangularity double null configuration. This divertor replaces the low triangularity Advanced Divertor installed in 1990. The design and analysis of the lower divertor is complete and hardware is being fabricated. Installation of the new divertor is scheduled to be completed by the end of 2005.**

The primary component of the lower divertor is a toroidally continuous flat plate. The plate is water cooled for heat removal. Three rows of graphite tiles are mechanically attached to the plate to shield it from plasma impingement. Owing to a concern over excessive erosion caused by plasma impingement, the through tile-face bolt holes have been eliminated from graphite in areas of high heat flux. The plate is water cooled for heat removal between shots and heated to 350°C with hot air and inductive current during vessel baking. The divertor plate is supported 100 mm from the vacuum vessel floor by two rows of 24 supports that must react the vertical loads due to halo currents. These supports are radially flexible to allow for differential radial thermal expansion between the divertor ring and the floor. The space below the plate forms a pumping plenum connecting the floor strike point to the lower cryo-pump. Upgraded floor tiles inboard of the plate will be installed to improve the target for the plasma strike point for outer leg pumping.

The divertor plate is to be fabricated in four 90 deg sectors from type 316 stainless steel. Each sector consists of two plate halves with three machined coolant channels and is joined together by spot welds and perimeter seam TIG welds. The vacuum tight 90 deg plate sectors are welded together inside the vessel to form a toroidally continuous ring. The water cooling/air bake-out lines connecting the 4 sectors into two 180 deg cooling circuits will be welded in situ.

Several plasma diagnostics will require some modification or relocation for integration into the divertor system.

Keywords–Tokamak, divertor, design

I. INTRODUCTION

The lower divertor of the DIII-D tokamak is being modified to provide improved density control of the tokamak plasma during operation in a balanced double null high triangularity configuration. This divertor replaces the much smaller Advanced Divertor installed in 1990. The design and analysis of the lower divertor is complete, hardware is being fabricated and installation is scheduled to start September 2005 for completion January 2006. In addition to the graphite tiles covering the divertor shelf, tiles for the vessel floor required redesign.

II. PHYSICS AND ENGINEERING REQUIREMENTS

A. Physics Requirements

The specified requirements ranged from a maximum heat flux of 13.2 MW/m^2 peak, to acceptable tile gaps of 0.6 mm and tile edge height alignment of 0.1 mm. Designated high heat flux areas were required to be covered with tiles having no bolt holes.. The divertor panels were designed for a 30% halo current with 2:1 toroidal asymmetry. A maximum panel heat load of 54 MJ was also identified. The physics requirements were based upon desired operational conditions and planned future experimentation.

B. Engineering Requirements

Using the physics requirements as a foundation, complementary engineering requirements were developed. The engineering requirements specified minimum water flow rate through the channels to achieve desired cooling as well as maximum allowable material stresses for specific operating conditions.

III. DIII-D DIVERTOR EXPERIENCE

The existing lower divertor or ADP ring was built in 1990 and was successfully employed up to the present. Between 1998 and 2000, two additional divertors were installed in DIII-D, inner and outer upper divertors. All three of these divertors have many similarities with each other and the new lower divertor, but all are unique as well. The basic construction techniques and manufacturing issues for the water cooled panels are shown below in Fig. 1.

IV. COOLING PANEL DESIGN

The new divertor ring is comprised of four 90 deg sectors or panels. Two sectors constitute one 180 deg cooling circuit. Ninety degree sectors were determined to be the largest which could fit into the vessel through available openings. The cooling panels consist of two stainless steel plates with water passages milled 1.3 mm deep on one side of each plate and then spot-welded together with the water passages facing each other. The material selected for the plates was 316 stainless steel due to its low magnetic permeability and good weldability. The 316 stainless was chosen over other available grades of stainless steel such as 304 as the 304 exhibited greater magnetic permeability after welding and machining.

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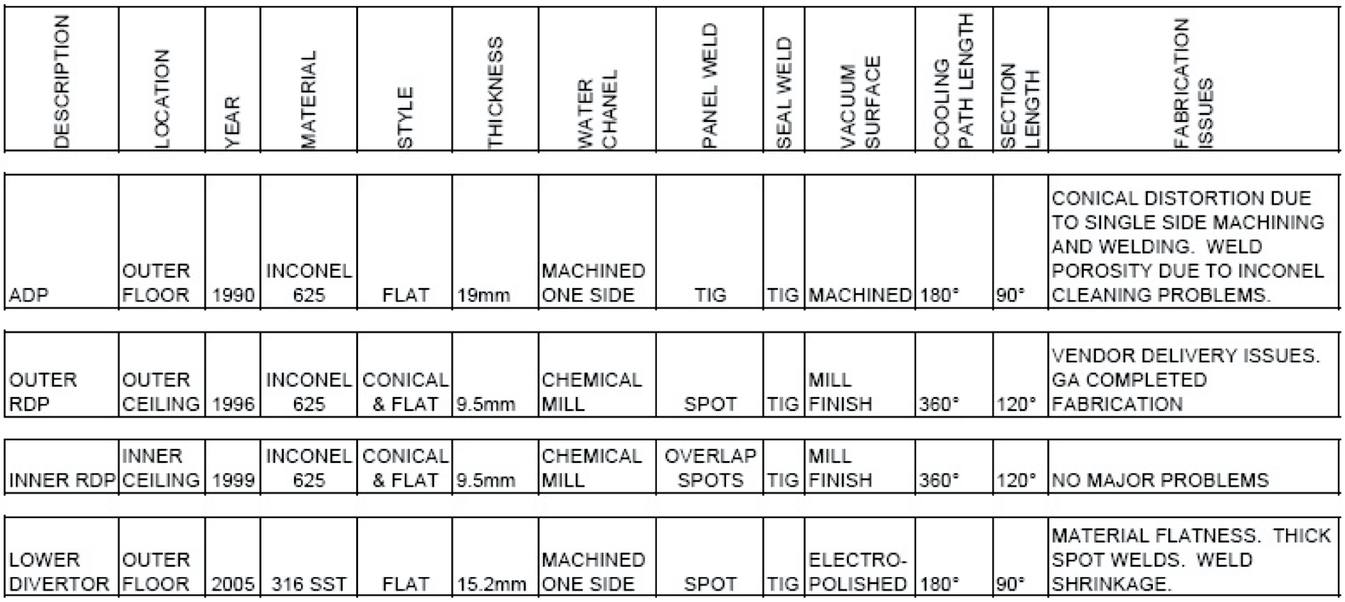

DESCRIPTION	LOCATION	YEAR	MATERIAL	STYLE	THICKNESS	WATER CHANEL	PANEL WELD	SEAL WELD	VACUUM SURFACE	COOLING PATH LENGTH	SECTION LENGTH	FABRICATION ISSUES
ADP	OUTER FLOOR	1990	INCONEL 625	FLAT	19mm	MACHINED ONE SIDE	TIG	TIG	MACHINED	180°	90°	CONICAL DISTORTION DUE TO SINGLE SIDE MACHINING AND WELDING. WELD POROSITY DUE TO INCONEL CLEANING PROBLEMS.
OUTER RDP	OUTER CEILING	1996	INCONEL 625	CONICAL & FLAT	9.5mm	CHEMICAL MILL	SPOT	TIG	MILL FINISH	360°	120°	VENDOR DELIVERY ISSUES. GA COMPLETED FABRICATION
INNER RDP	INNER CEILING	1999	INCONEL 625	CONICAL & FLAT	9.5mm	CHEMICAL MILL	OVERLAP SPOTS	TIG	MILL FINISH	360°	120°	NO MAJOR PROBLEMS
LOWER DIVERTOR	OUTER FLOOR	2005	316 SST	FLAT	15.2mm	MACHINED ONE SIDE	SPOT	TIG	ELECTRO-POLISHED	180°	90°	MATERIAL FLATNESS. THICK SPOT WELDS. WELD SHRINKAGE.

Figure 1. General Atomics DIII-D divertor history.

Through all machining and welding, plate and panel flatness was tightly controlled, as a flat end result was necessary to facilitate tile alignment (Fig. 2). Through plate holes were available every 5 deg (Fig. 3), allowing for additional clamping during plate and panel machining, enabling greater flatness control.

Figure 2. Machining of cooling channels.

The two plates are each 7.6 mm thick, giving a 15.2 mm total panel thickness. The thickness of the plates was based primarily on material strength characteristics and the maximum halo current forces. Each 90 deg panel was spot welded together in approximately 200 places to provide sufficient strength to allow the plates to act as one stiff panel during disruptions and halo current events and to react the water pressure of 75 psid. Due to the thickness of the material, no AWS standards covered the spot welding that was required. In order to determine machine settings, a weld schedule was developed. Each spot weld showed adequate strength (~12.5 ksi shear), but also caused noticeable material deformation (Fig. 3).

While the spot welds provided sufficient plate to plate strength, panel vacuum sealing was also required. The panels were sealed via TIG welds that ran the perimeter of the panels. In order to fasten tiles to the panels, inconel studs were welded to the inner and outer edges (in the low high flux heat zones) and bolt sleeves were machined through and seal welded in the high heat flux areas to allow for through plate fastening (Fig. 4). Inconel studs were chosen over stainless steel studs as galling problems with stainless steel studs have arisen in previous applications.

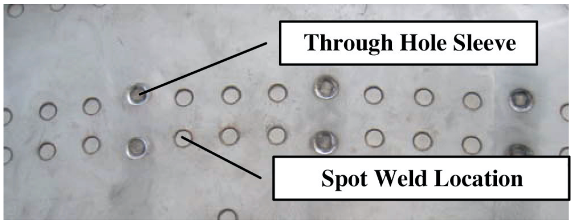

Figure 3. Spot weld and through hole locations on panel.

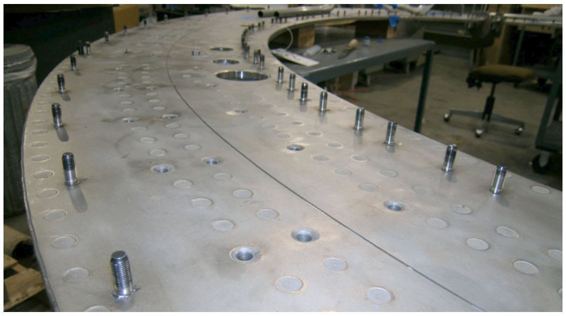

Figure 4. Tile studs on divertor panel.

V. PLASMA FACING TILE DESIGN

A. Divertor Shelf Tiles

The divertor shelf is covered by three rows of Union Carbide ATJ graphite tiles. These tiles were required to have no fastener holes visible to the plasma in specific high heat flux zones as defined by the physics requirements. The inner most divertor shelf tile is held onto the panel by two studs welded to the panel. The middle row tile on the shelf is attached by two bolts that come from the underside of the panel. The outer row shelf tile is secured to the panel through the use of one bolt and one welded stud. This tile arrangement requires access to the underside of the divertor shelf for installation and removal of either middle or outer row shelf tiles. A typical divertor shelf inner row tile in shown in Fig. 5.

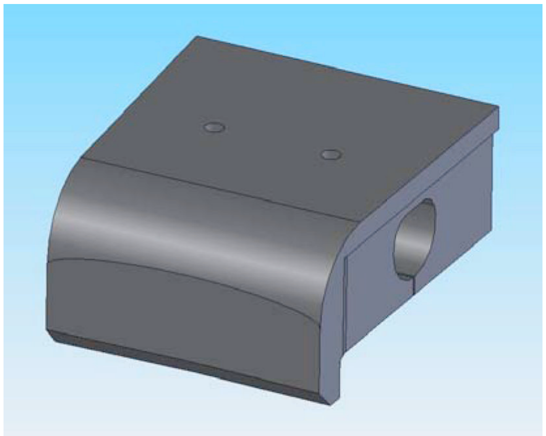

Figure 5. Divertor shelf tile.

B. Floor Tiles

The new lower divertor shelf covers a 41 cm radial width leaving approximately 22 cm of the DIII-D vessel floor inboard of the shelf. This floor space is to be covered by graphite tiles which have no fastener holes or other sharp exposed edges. Two options were evaluated to fit the requirement; either cover up any fastener holes with some type of graphite or CFC plug (Fig. 6) or hold the tiles down at their extreme ends radially (Fig. 7).

Both tile designs were prototyped and tested under various conditions. Tiles with plugs were shaken on a vibration table and baked to test the effects on plug torque. While the tile plugs performed well during this testing, basic handling and torquing of the plugs revealed the mechanical weakness of the threaded plugs. One ATJ graphite plug sheared at 8 in.-oz, which was to be the design torque. No positive restraining device was conceived of for the plugs which was another shortcoming.

The long hold down system employed one large stainless steel bar which clamped the edges of two tiles radially and was fastened to the floor at the radial edges of the tiles. This design provided for greater tile edge to edge matching as this was a common clamp point. This design also allowed for smooth surface tiles with no bolt holes. One area of concern with the long hold down bar which was analyzed was the adequacy of thermal conductivity between the tiles and the floor due to uneven pressure distribution along the length of the bar. The stainless steel bar is sufficiently stiff and the thermal conductivity was determined to be acceptable along the length of the bar, but longer bars would require greater stiffness.

The arch type tile system was chosen to cover the vessel floor due to improved edge alignment and the elimination of the unproven plugs.

C. Tile Thermal Analysis

Tile thermal analysis was performed using both ANSYS and COSMOSWORKS models. Finite element analysis was employed as ATJ material properties change non-linearly and significantly with temperature from 0 to 2500°C. The design heat flux specifications was a triangular distribution with a 11.2 MW/m^2 peak on the divertor shelf and 13.2 MW/m^2 peak on the vessel floor for 10 s. Thermal analysis was done on both the divertor shelf tiles and the new floor tiles. The relatively poor thermal conductivity of ATJ graphite combined with the desired high heat flux being deposited over a small area (5.5 cm width) resulted in extremely high local temperatures on the tile surfaces (Fig. 8). This temperature was known to be well past the point of ATJ ablation and allowable stresses in the tiles were well exceeded.

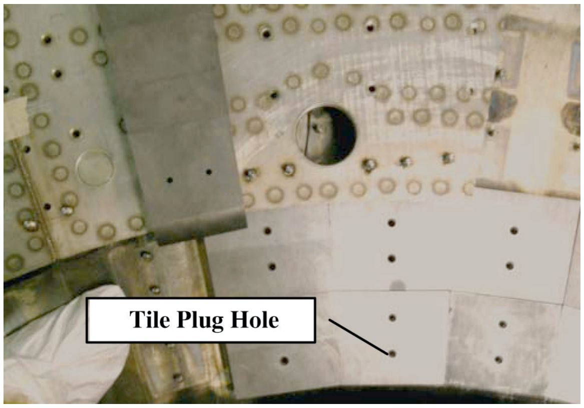

Figure 6. Plug type tile test installation (no plugs installed).

Figure 7. Arch type tile test installation.

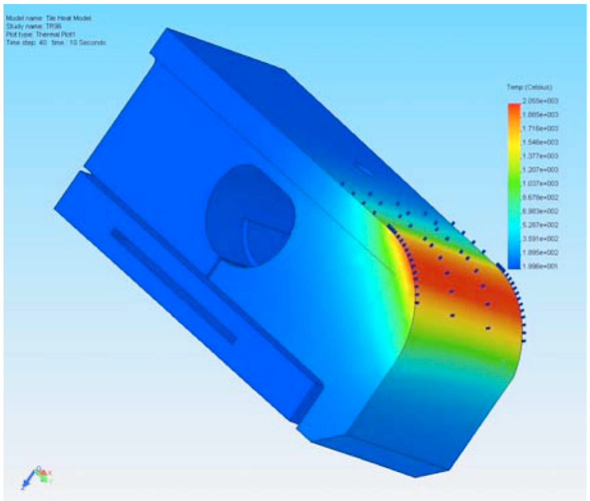

Figure 8. COSMOSWORKS tile thermal analysis.

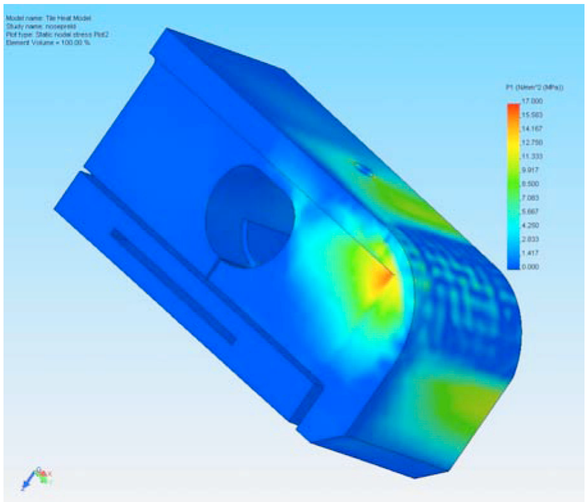

Figure 9. COSMOSWORKS stress analysis.

VI. INSTALLATION

Based upon the tile damage caused by the desired heat flux, analysis was done at reduced heat flux levels to identify potential operational limits. Heat flux was gradually reduced until thermal stresses were within allowed limits. Thermal stresses in the tile decreased much faster than linearly with decreasing tile temperature. Cases were evaluated for both 5 and 10 s shot lengths. Between shots, the tiles are cooled by the actively cooled divertor shelf and the actively cooled vessel floor. Figs. 8 and 9 show representative COSMOSWORKS analysis on the inner divertor shelf tile showing cases where the largest triangular heat flux does not exceed tile allowable stresses. The maximum tensile stress on the tile occurs where the temperature gradient is the largest. The small slit under the hold down hole in the tile relieves mechanical stresses caused the hold down nuts used for the clamping of the tile to the divertor shelf.

A. *Hi-Bay Preparation*

The four 90-deg panels were test fit in a large open area (Hi-Bay) and studs for tiles, support legs and magnetic diagnostics were electric discharge welded to them (Fig. 10). Upon completion of the stud welding and cleaning, the panels were vacuum leak tested for the final time prior to vessel installation. Stud locating, which had previously relied upon mylar templates for location, was improved through the use of small CNC machine marks which had been placed during final panel machining. Once the studs have been welded to the panel, a handful of ball transfers will be attached to the plate to facilitate vessel entry.

B. *In-Vessel Installation.*

At a weight of approximately 200 lbs each, the panels will be moved by overhead crane to the side of the vessel. At this point the panels will be loaded onto a large aluminum transfer plate to allow the panels to roll on their ball transfers into the vessel. Once inside the vessel, the panels are flipped over and lowered onto support post which will allow for the panels to be assembled and welded into the ring configuration. The divertor ring will then be lowered into its final position and water lines will be welded in place.

Figure 10. Divertor ring in hi-bay.

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